

SEICHES IN LOWER LAKE MICHIGAN IN MAY, 1912.

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The hydrographic records made at Milwaukee and Chicago during May, 1912, under the supervision of the U. S. Lake Survey Office, indicate the occurrence of unusually marked seiches in lower Lake Michigan on the 19th, 20th, and 21st. It is my intention to correlate if possible, these hydrographic records with the records of atmospheric conditions which prevailed during that period at Milwaukee, Madison, Grand Haven, and Chicago. This will afford arguments for making deductions as to the probable cause of these unusually large and rapid fluctuations in the lake level in the vicinity of Milwaukee and Chicago.

The gage from which the hydrographic records at Milwaukee were obtained is stationed at the end of one of two nearly parallel piers, 350 feet apart, which project in an easterly direction from the middle of the shore of the bay toward the center of the bay, and are 1,800 feet in length. These piers form an outlet for the Milwaukee River which empties into the bay. The bay has a lateral depth of about $1\frac{1}{2}$ miles, measuring from a line drawn between the two extreme ends, the line between the extremities being about $5\frac{1}{2}$ miles long. A breakwater extends southward from near the northern extremity and affords a protection for nearly half the bay. Thus it will be seen that the location of the gage is a good one for obtaining measurements of the water level in Milwaukee Bay.

The two principal meteorological elements advanced as being factors in the causes of seiches are the combined action of velocity and direction of the wind, and large and sharp fluctuations in atmospheric pressure.

An examination of the wind records made at near-by stations during this period seems to indicate that the wind was not the principal factor in the production of these seiches. The velocities during this period were mostly light to moderate, and no severe gusts of wind were recorded. That a higher level of the water surface existed at Milwaukee and Chicago during the latter part of the period of May 18 to 21, inclusive, is shown by the hydrographs of those places. This was doubtless due to the fact that onshore winds prevailed during a greater part of the period in question. In addition to the change in the general level, due to onshore winds, it is probable that sudden variations in the direction and velocity of these winds may have constituted impulses which, added to and working in harmony with impulses caused by rapid variations in atmospheric pressure, operated to increase the amplitude of oscillation in the water level to a considerable extent.

While the records indicate that the principal cause of these seiches was the variation in atmospheric pressure during this period, it is not believed that the large oscillations in the water level were due entirely to individual momentary differences in atmospheric pressure over the water surface, but were due rather to the cumulative effect of a series of such differences timed at proper intervals so that each impulse thus given to the wave augmented its movement to some extent, finally producing oscillations of large amplitude. The greatest fall in pressure recorded within one hour at Milwaukee during this period, as shown by the barograph trace, could not of itself have affected the water sufficiently to cause sudden rises of nearly two feet, as are shown by the hydrograph of that place. Several very decided and rapid

changes in atmospheric pressure were recorded during this period of seiches, the most marked of which occurred during the forenoon of the 20th. There was a rapid fall of 0.20 inch in atmospheric pressure at 9 a. m. on that day, which in water equivalent would equal about 0.22 of a foot, and assuming that the atmospheric pressure over the bay at that time was 0.20 of an inch lower than that over the lake, the effect of this difference in pressure between the two places would have raised the water level in the harbor about 0.2 of a foot. To this increase in water level must be added the effect the contour of the shore of the bay would have in raising the level still further, due to the water's being confined to a space of limited area and depth. But the hydrographic record made at Milwaukee shows among other rapid changes, two quick rises of nearly two feet in the water level which were immediately followed by falls of $2\frac{1}{2}$ feet, and it does not seem possible that this difference in atmospheric pressure, granting that the difference was maintained long enough to permit the waters to fully respond to it, could of itself have caused seiches of this magnitude.

The most reasonable evidence offered for the solution of this problem apparently lies in the unusually large number of rapid oscillations in atmospheric pressure, following the large variations already noted, which are shown by the barograph traces from stations in the vicinity of Milwaukee to have occurred during this period. Let us assume that the sudden fall in atmospheric pressure of 0.18 of an inch, as recorded at Milwaukee, and indicated by the barograph trace of that station as having occurred at 9 a. m. on the 19th, set in motion a wave of considerable dimensions, which on entering the bay raised the level of the water there 0.2 of a foot. Let us assume further that this atmospheric depression then passed out over the lake, approximately at about the same time that the water in the bay, which was in a state of unstable equilibrium with the water outside, began a return current toward the lake. The arrival of the barometric depression over the lake would have the effect of raising the water level there in a manner similar to that which took place in the bay when the depression was centered over that place. Thus the combined action of these two forces would probably have formed a wave of considerable head outside the bay. Furthermore, the barograph trace indicates that a sudden increase in atmospheric pressure took place over the bay immediately following the depression mentioned above, and it seems reasonable to assume that this increase in pressure occurred at about the same time that the other two forces were operating. If this rise in atmospheric pressure over the bay did occur at the proper time, it would, by its depressing effect on the water in the bay, still further increase the height of the wave. It is probable that this wave now would have sufficient energy to set in motion a series of slow surges in and out of the bay which, if no impulses were received to further augment its movement, would gradually diminish in extent due to the frictional resistance of the water particles one upon another and on surrounding media.

But the Milwaukee barograph trace shows a series of sharp rises and falls in pressure following the unusually large change at 9 a. m. on the 19th, and the hydrographic record indicates that the amplitude of oscillation of this great wave increased after 9 a. m. of that day, the extremes in the stage of water being recorded in the late afternoon. It seems very probable that the majority of the additional variations in atmospheric

pressure, as recorded by the barograph, were so timed as to work in harmony with the rhythmic movement of this immense wave, although there probably were some oscillations in the pressure that worked out of harmony with its movement. Also that the harmonious artificial impulses thus received by the water surface caused the wave to grow larger and larger, not in regular progression but in an irregular manner, until the morning of the 20th when the level of the water in the bay reached the highest point recorded during this series, and was immediately followed by a rapid fall of 2.5 feet. If the majority of these oscillations in atmospheric pressure following the first primary change, had been so timed as to work out of harmony with the rhythmic movement of the wave, every change so timed would have had a nihilating effect on the head and amplitude of oscillation of the wave and stages approaching the normal would probably have been recorded.

But the hydrograph shows a variation in the amplitude of oscillation of the wave, that is, large sudden rises and falls in the stage were interspersed with oscillations of limited extent. This is probably explained by the fact that the wave in its travel encountered barometric variations that worked in opposition, by a variable extent, to the wave's rhythmic movement and thus reduced the head of the wave by that amount. To these effects must also be added the influence of variations in wind direction and velocity, which, as previously indicated, would also increase or decrease the amplitude of oscillation of the wave.

A comparison of the barograph trace with the hydrograph as made at Milwaukee shows that some large, sudden changes in atmospheric pressure were not accompanied by corresponding increases in the amplitude of oscillation of the wave at that particular time, while some smaller changes in pressure, which probably were timed at more proper intervals to agree with the rhythmic movement of the wave, were followed by some of the most pronounced seiches. This was probably due to the fact that the sudden, large changes in atmospheric pressure were so timed with respect to the movement of the wave as to give a modified impulse. For example, if the wave were approaching the bay at a time when a sudden sharp fall in atmospheric pressure were approaching from the west, they both might have been so timed as to work exactly in harmony and produced a very high stage, but if the barometric pressure over the bay had declined only half way at a time when the water reached its maximum stage in the bay, the further fall in barometer over the bay would have had a reverse effect on the water level there, as the wave would already have begun to recede. In contrast to this, a smaller sharp fall in pressure might have arrived over the bay at such a time as to give the wave the full benefit of its effect for a higher stage.

The arguments in this article appear to be strongly supported by a comparison of the barograph trace with the hydrograph as made at Milwaukee. The barograph trace shows that, in general, sharp fluctuations in pressure began several hours before the largest fluctu-

ations in the water level, and ceased several hours before the latter decreased in amplitude of oscillation.

The limited data found available on this subject offers the following conclusions:

That these seiches were caused by the movement of an immense wave or surge in and out of the bay.

That an unusually rapid and large change in atmospheric pressure probably gave the wave its original energy for the production of high stages in the bay.

That this wave reached such large proportions because of the fact that the majority of impulses due to atmospheric elements were so timed as to operate in harmony with the wave's rhythmic movement.

That the variations in atmospheric pressure apparently afford the best argument as the principal cause of these seiches.

The following notes on wind direction and velocity at Milwaukee during the period may be of interest.

May 18.—Wind steady southwest, occasionally into west or northwest, until 1 p. m., when it shifted to west, and to northwest at 4 p. m., through north into northeast by 6.50 p. m. and held steady northeast until past midnight, velocities light to moderate and steady, except light squalls between 10 and 11.15 a. m.; maximum velocity for 5 minute period being 29 miles.

May 19.—Wind light and steady northeast until 8.30 a. m., when it shifted to southeast through east, and was variable 9 a. m. to 10 a. m. with very light velocities. At 10.20 a. m. there was a sudden squall from east, 31 miles in 5 minutes, 35 miles in 1 minute, but wind soon again became light, held northeast to southeast until 1 p. m., after which quite steady northeast until midnight. Velocities were steady and increasing until 11.35 p. m., when 27 miles occurred in 5 minutes.

May 20.—First two hours northeast with some east and southeast, velocity decreasing; 2 to 3 a. m. wind variable, rather steady southeast 3 to 5 a. m., south at 5.15, and southwest at 5.45 a. m., then mostly north until 8.30 and northeast to 8.55, when it shifted suddenly to southeast, accompanied by a light puff at 8.50 of 24 miles in 5 minutes; 9 to 10 a. m. wind variable and light; 10 to 11 mostly north with occasional northeast and northwest; 11 a. m. to 1 p. m. northeast, after which it shifted between north and northeast until midnight. Velocity light and steady at all times, even during a thunderstorm at 10.20 p. m., when wind shifted suddenly to west for a few minutes.

May 21.—Light velocities throughout 24 hours and no squalls; shifted between north and northeast until 8 p. m., after which it held quite steady northeast. During the early morning hours there were occasional shifts into northwest, but these were short in duration.

NOTE.—In connection with the high stages and large fluctuations in the water level of the bay on those days, as shown by the hydrograph at Milwaukee, the effect of the contour of the shore of the bay must not be overlooked. The immense amount of water which forms a wave with even a small head when out in the lake, upon entering the bay, will raise the level of the water there considerably, due to the fact that the water is forced into a space of limited area and depth, and that the momentum of such a wave is so great that it piles the water up in the bay to high levels before its inertia is overcome.